NOTE

Restoration of Real-World Motion-Blurred Images

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Estimating the PSF of a real-world motion-blurred image is an essential step in the restoration process. To estimate the PSF, some techniques assume that it is a spatially invariant square pulse, and extract the blur extent from the zero-crossings of the averaged power spectrum. Some techniques make use of special features such as isolated point objects or sharp edges in a homogeneous background. Recently, sophisticated methods based on maximum likelihood estimators have been developed for estimation of symmetrical PSFs. In actual applications, we often encounter motion-blurred images which have asymmetrical PSFs. There are also no special features such as isolated points. These images present challenges which are not satisfactorily met by the above techniques. In this paper, we first study the error characteristics due to the use of inappropriate PSFs. On the basis of the results, we develop a procedure for estimating (possibly) asymmetrical PSFs of real-world motion-blurred images. The procedure starts with a preliminary restoration using a ramp PSF. The result will indicate if a ramp PSF, a square pulse PSF, or a trapezoid PSF is appropriate, and also provide an estimate for the blur extent of the appropriate PSF. Images restored according to the procedure are practically free of ghost or ringing patterns. The effectiveness and practicality of the proposed procedure is tested using a few real-world images blurred with unknown PSF.

I. INTRODUCTION

For the purpose of restoration, it is often assumed that a motion-blurred image \( g \) can be modeled as

\[
g = f * h + n,
\]

where \( f, h, \) and \( n \) are the original scene, linear shift-invariant point spread function (PSF), and noise, respectively. When the PSF is known, many techniques are available for estimating \( f \) from \( g \). However, for a real-world motion-blurred image, the PSF is generally unknown. It is then necessary to assume a PSF to carry out the restoration, and methods have been developed for estimating PSFs from the blurred images.

Earlier papers often assumed that PSFs of motion-blurred images are square pulses and estimation of the width (blur extent) of the assumed square-pulse PSF was then the key issue. One class of methods [1–4] estimates the blur extent by measuring the separations of zero lines in the averaged power spectra. The success of such methods depends much on the validity of the assumption that the PSF is indeed a square pulse, and that it is spatially invariant so that the averaged Fourier transform will show zero-crossings.

Rosenfeld [5] has suggested that the PSF of a motion-blurred image may be estimated from the blurred intensity distribution of a point object or a sharp edge against a homogeneous background. Such methods are unfortunately not applicable to images where such features are not present.

Significant contributions have recently been made by Tekalp et al. [6] and Tekalp and Kaufman [7]. By autoregressive modeling and assuming white-Gaussian-noise errors, they applied the maximum likelihood (ML) criterion to the estimation of PSF. In [6], an example restoration of a real-world focussing-blurred image has demonstrated the potential of their ML method. Their method is applicable to general symmetric PSFs. The restriction to symmetric PSFs is due to the fact that the phase of the PSFs cannot be determined by the ML method.

Restoration errors have been studied by various authors [8–10]. In [8], “ringing artifacts” were described. Woods attributed the ringing artifacts to boundary problems. References [9, 10] analyzed “ringing effects” (caused by the regularization procedure) which have a distinct appearance from the ringing artifacts.

Lim et al. [11] have presented a mathematical analysis of the error pattern in inverse and pseudo-inverse restorations of square-pulse blurred images. They identified two error components: (1) edge errors which arise from
the nonperiodicity of the image, and (2) restoration errors which arise from the use of pseudo-inverse filter. The edge errors show up in periodic bands across the whole image. The edge errors resemble the "ringing artifacts" of [8]. Lim et al. [12] and Tan et al. [13] showed how the edge errors may be practically removed by preprocessing or windowing. We shall therefore not be concerned with edge errors in this paper. The restoration errors resemble the "ringing effects" of [9, 10]. The restoration errors are the result of assuming a PSF for restoration which deviates from the true blurring PSF. For instance, a pseudo-inverse (regularized) restoration using the filter $H^*/(HH^* + \gamma)$ may be regarded as equivalent to an inverse filtering with the transfer function $H + \gamma/H^*$. The deviation $\gamma/H^*$ of the assumed transfer function from the true transfer function $H$ gives rise to the restoration errors.

When the assumed- and true-PSFs are symmetrical, the restoration errors show up as symmetrical ringings around prominent features in the image. In restoration of motion-blurred images obtained with a camera, another type of restoration error is often detected. This type of error is characterized by an inverted image appearing beside every prominent feature, often known as a "ghost." If the true-PSF is $H$ and the assumed-PSF is $H_a$, a Wiener filter restoration of the image is given by a convolution of the original image with the kernel

$$DFT^{-1}\left(\frac{H^*H_a}{HH_a + \gamma}\right).$$

Since both $H$ and $H_a$ are phaseless, the Wiener filter is phaseless, and the kernel is symmetrical. Ghosts are therefore not possible when both the assumed- and true-PSFs are symmetrical. Their frequent appearance therefore indicates that the PSFs of some classes of motion-blurred images may have significant asymmetry. Recent ML techniques [6, 7] would not be applicable to them.

The first part of this paper is devoted to a study of the relation between the characteristics of restoration errors and the deviation of the assumed-PSF from the true-PSF. An interesting observation is made. When assuming a square-pulse PSF for restoration (as is usually done in many restoration techniques), the error characteristics strongly reflect the features of the assumed-PSF but reveal little about the true-PSF. However, we show that when an asymmetric PSF, such as a ramp, is assumed for restoration, the error characteristics turn out to be very informative about the true-PSF. On the basis of this observation, we develop a simple and economic procedure for restoring real-world motion-blurred images. This procedure has proven to be effective and is described in the second part of this paper.

II. PROTOTYPE PSFs

For motion-blurred images taken with a camera, we found that the blurring PSF can usually be adequately approximated by a trapezoid. To cover a range of representative shapes, we shall adopt the following five prototype PSFs for this study. They are

(a) Reverse ramp: $RR_i = M - i$, for $i = 0, \ldots, M - 1$ (2)

(b) Reverse trapezoid: $RT_i = 2M - i$, for $i = 0, \ldots, M - 1$ (3)

(c) Square pulse: $SP_i = 1$, for $i = 0, \ldots, M - 1$ (4)

(d) Forward trapezoid: $FT_i = M + i$, for $i = 0, \ldots, M - 1$ (5)

(e) Forward ramp: $FR_i = i + 1$, for $i = 0, \ldots, M - 1$ (6)

where $N$ is the number of pixels across the width of the image, $M$ is the blur extent, and all the PSFs have value 0 for $i = M, \ldots, N - 1$. The above PSFs may have to be normalized for actual applications. These five PSFs may be regarded as crude models for blurring by uniform, accelerated (decelerated), and highly accelerated (decelerated) motions of the camera relative to the scene.

In our restoration work, we have in fact used a wide range of trapezoidal PSFs of various aspect ratio and skewness. For this paper, we shall for simplicity restrict ourselves to the above five prototype PSFs which together exhibit all the main characteristics of restoration errors which we intend to discuss. Based on a general understanding of the relation between the restoration error characteristics and PSF mismatch, fine tuning in the shape of the assumed-PSF beyond the five prototypes for improved restoration of specific images may be easily carried out.

III. CHARACTERISTICS OF RESTORATION ERRORS

In two previous papers [11, 13], we have shown that the discrete Fourier transform (DFT) of a blurred image $g$ may be written as

$$G = FH + E + N,$$  (7)

where $F$ and $H$ are the DFTs of $f$ and $h$, respectively, $E$ is the edge error term, and $N$ is a random noise term. The term $E$ gives rise to edge errors, which can fortunately be successfully suppressed in most cases with the optimal window of [13]. After windowing, the images are restored
using the Wiener filter

$$\frac{H_0^*}{H_0H_0^* + \gamma} \quad (8)$$

where $H_0$ denotes the DFT of the assumed-PSF, $H_0^*$ the complex conjugate of $H_0$, and $\gamma = 0.005$ according to the recommendation of [11].

Neglecting the edge error and the noise terms in Eq. (7), we can write the restoration $\hat{f}$ as a convolution of the original scene $f$ and a Green's function $S$ as defined below.

$$\hat{f} = f \ast \text{DFT}^{-1} \left( \frac{HH_0^*}{H_0H_0^* + \gamma} \right)$$

$$= f \ast S, \quad (9)$$

where $H$ denotes the DFT of the true-PSF which is unknown. The quality of the restored image depends on how close $H_0$ is to $H$.

The Green's function $S$ gives a very concise description of the characteristics of the restored images—it shows how a point object in the original scene $f$ would appear in the restored image $\hat{f}$. The Green's functions for various combinations of the five prototype PSFs are computed and displayed in Figs. 1–3. In Fig. 1, the true-PSF is a square pulse with an extent of 16 pixels. Figures 1a–1c show the Green's functions for forward-ramp assumed-PSFs of extents 12, 16, and 20, respectively. Figures 1d–1f and 1g–1i are similar to Figs. 1a–1c except that they are for reverse-ramp assumed-PSFs and square-pulse assumed-PSFs.

Figures 1a–1f show that when the true-PSF is a square pulse, the Green's function $S$ is not sensitive to the extent of the forward- or reverse-ramp assumed-PSFs. In all cases, the Green's functions show a large positive peak and a large negative peak separated by the blur extent of
the true-PSF. These Green's functions imply that an image blurred by a square-pulse PSF when restored using a ramp PSF will show a negative (inverted) version of the scene, or ghost, superimposed on the true scene. For a forward-ramp assumed-PSF, the ghost scene is displaced by one blur extent of the true-PSF to the left of the true scene, while for the reverse-ramp assumed-PSF, the ghost scene is displaced by one blur extent of the true-PSF to the right of the true scene. These observations show that the blur extent of the true-PSF may be determined by measuring the displacement of the ghost.

Figures 1g–1i show the rather surprising results that square-pulse assumed-PSFs generally give restorations which exhibit ringing patterns even when the true-PSF is a square pulse. When the assumed-PSF has the correct blur extent, multiple negative peaks are observed to both sides of the central positive peak (Fig. 1h). When the assumed-PSF has a wrong blur extent, much stronger ringing patterns are observed (Figs. 1g and 1i). This gives rise to a very disturbing sequence of multiple positive and inverted scenes superimposed on the true scene. Measurements carried out in Figs. 1g–1i show that the ringing has a wavelength equal to the blur extent of the assumed-PSF.

Figures 2a–2i show the Green's functions obtained with the same assumed-PSFs as in Figs. 1a–1i but with a 16-pixel forward-ramp as the true-PSF. Figures 2a–2c show that when the true-PSF is a forward-ramp, the restored images obtained using a forward-ramp assumed-PSF will in general be good even when a wrong blur extent is used. Figures 2d–2f show that with a reverse-ramp assumed-PSF, the restored images will show a badly smeared-out true scene next to a clear inverted scene (ghost). With square-pulse assumed-PSFs, the restorations are poor with strong ghosts and severe ringing. Again we note that the ringing wavelength is equal to one blur extent of the assumed-PSF.

Figures 3a–3i show the Green's functions obtained with the same assumed-PSFs as in Figs. 1a–1i but with a 16-pixel forward-trapezoid as the true-PSF. Figures 3a–3i show that when the true-PSF is a forward-trapezoid, the characteristics of the restorations are intermediate between those obtained when the true-PSF is a ramp or a square pulse. This is not surprising as a trapezoid may be
obtained by combining a ramp with a square pulse. Ghosts occur when ramp assumed-PSFs are used. When the polarities of the assumed- and true-PSFs agree (both forward), the ghost is weaker than the true scene and is displaced to the left by one blur extent of the true-PSF. When their polarities are opposite, the ghost is the stronger and appears to the right of the true scene. As in the previous cases, when square-pulse assumed-PSFs are used, strong ringing occurs. The wavelength is again equal to one blur extent of the assumed-PSF.

IV. A NEW PROCEDURE FOR ESTIMATING PSFs OF MOTION-BLURRED IMAGES

From these results, we deduce that when restoring a real-world motion-blurred image, some exploratory restorations may be carried out using assumed-PSFs, in order to determine the shape and blur extent of the true-PSF, guided by the characteristics of the exploratory restorations obtained. The estimated true-PSF may then be used for the final restoration.

On the basis of the results of the last section, we may conclude that a square-pulse PSF is not a suitable assumed-PSF for exploratory restoration. The main reason is that the ringing pattern in square-pulse PSF restorations has a wavelength equal to the blur extent of the assumed-PSF and tells us very little about the shape or the blur extent of the true-PSF.

On the other hand, a ramp assumed-PSF is very useful for exploratory purposes. If the true-PSF is a square pulse or trapezoid, a strong ghost will appear displaced by one blur extent of the true-PSF from the true scene. The appearance of the ghost then strongly suggests that the true-PSF is a square pulse or trapezoid; more importantly, the displacement of the ghost accurately gives the blur extent of the PSF.

To illustrate some of these points, we show Figs. 4 and 5, which are restorations of an image blurred with a 16-pixel forward-trapezoid PSF. Figure 4 was the exploratory restoration obtained with a 20-pixel forward-ramp assumed-PSF. A ghost of weak intensity appears 16 pixels to the left of the true scene. Checking against Figs. 1c, 2c, and 3c, we may conclude that the image was blurred with a 16-pixel PSF. Figure 5 shows the restoration ob-
FIG. 4. A restoration obtained with a 20-pixel forward-ramp assumed-PSF. The true-PSF of the blurred image is a 16-pixel forward trapezoid. The ghosts allow the blur-extent of the true-PSF to be accurately determined.

FIG. 5. The same blurred image of Fig. 4 restored with a 16-pixel square-pulse PSF. The ringings to the right of prominent features indicate that the true-PSF is likely to be a forward trapezoid.

V. SOME REAL-WORLD MOTION-BLURRED IMAGES RESTORED

In this section, we apply the restoration procedure to the two real-world motion-blurred images shown in Figs. 6.

FIG. 6. A motion-blurred photograph taken on diapositive by panning the camera.
FIG. 7. Another motion-blurred photograph taken on an Ektachrome slide by panning the camera.

6 and 7. Figure 6 was taken on a diapositive and Fig. 7 was taken on an Ektachrome slide. Blurring was caused by panning the camera when the shutter was being released. The images were digitized with a monochrome video camera with back illumination.

In Fig. 6, the text is badly blurred, but the sprocket holes and the lettering "LFC" on the diapositive are clearly visible. Figure 8 shows the image restored using a forward-ramp. Ghosts of the text in the image are clearly visible. Measurements indicate that the blur extent varies from 26 pixels for the first row of text to 28 pixels for the last row. The variation of the blur extent is very systematic, which suggests that it is not due to random errors due to noise. In view of this, we may, if desired, attempt to restore the upper and lower halves of the image with assumed-PSFs of different extents. However, for simplicity, we shall use an average blur extent of 27 pixels for later restorations. An interesting side observation is that the forward-ramp restoration preserves the image of the sprocket holes and the lettering "LFC" fairly well. There is a simple explanation for this. We may consider an unblurred image to be a scene "convolved" with a 1-pixel square-pulse PSF. A restoration with a forward-ramp PSF will then generate a ghost scene displaced one pixel to the left of the true scene. The result will therefore just be an edge-enhanced version of the original image.

We next restore Fig. 6 with a 27-pixel square-pulse PSF and obtain Fig. 9. Ringing is now observed on the right of the true scene, which suggests a forward-trapezoid PSF. A final restoration with a forward-trapezoid PSF yields Fig. 10. The ringing is suppressed and a fairly good restoration is obtained.
In this paper, we have used images of signboards so that the quality of restoration can be easily judged by the readability of the restored images. During our research, we have also obtained good results restoring complicated images using our procedure. It may be worth noting that in our research, we have encountered true-PSFs which are most accurately approximated by square pulses, trapezoids, and also ramps, although only square pulses and forward trapezoids showed up in the above examples.

VI. SUMMARY AND CONCLUSIONS

Estimating the PSF of a real-world motion-blurred image is an essential step in the restoration process. The technique suggested by Rosenfeld [5] is applicable to blurred images which contain special features such as point objects or ideal edges in homogeneous background. Frequency domain techniques such as that proposed by Welch [1] or Cannon [2] are applicable when the image is blurred by a spatially invariant square-pulse PSF. The sophisticated maximum likelihood techniques developed recently by Tekalp et al. [6, 7] are applicable to images with symmetric PSFs. In our work, motion-blurred images taken by camera on films or slides are often found to have asymmetric PSFs which may not be spatially invariant. The above-mentioned methods are not directly applicable or optimal for many of the images we have encountered.

We first studied the error characteristics due to mismatch in the assumed- and true-PSFs. We considered five prototype PSFs: forward ramp, forward trapezoid, square pulse, reverse trapezoid, and reverse ramp, which may be considered simple models of blurring by accelerated motion. Our experience shows that such PSFs are adequate for restoration of most real-world motion-blurred images. The main findings are that (1) mismatch in the assumed- and true-PSFs causes ringing and ghost error patterns, (2) square-pulse assumed-PSFs are poor for exploratory restorations as the error patterns are not informative about the true-PSF, (3) ramp assumed-PSFs are useful for exploratory restorations as the error pattern offers strong hints as to the characteristics of the true-PSF.

Based on the above, a procedure for PSF estimation is proposed. The blur image is first restored with a Wiener filter assuming a forward-ramp PSF. Based on the characteristics of the ghost and ringing patterns, the blur extent and the shape of the true-PSF may be estimated. The blurred image is again restored with the estimated PSF, and the residual error pattern is scrutinized for ways of refining the estimated PSF.

Restorations of simulated and real-world motion-blurred images have been presented to illustrate the procedure. Our experience suggests that the five prototype
PSFs provide adequate approximations to the PSFs of common motion-blurred images. Our findings on the relation between error characteristics and PSF mismatch (summarized in Figs. 1–3) provide useful guides for further refinements in the shape and skewness of the PSF beyond the prototypes.

The Wiener filter, which is computationally economical, was found to be adequate for the purpose of PSF estimation by our procedure. After the true-PSF has been determined sufficiently accurately, other methods of restoration which are more accurate or appropriate to the specific image or PSF may be used. Furthermore, when the PSF varies significantly over the image, it may be better to restore different parts of the image separately, according to the variation of the PSF. Our method allows this since it can determine the PSF even when it is not spatially invariant over the image.

REFERENCES